MICROWAVE ELECTRON ACCELERATORS IN THE MEDIUM ENERGY RANGE

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Summary

Microwave electron accelerators in the 3 MeV to 1 GeV range are being developed and produced for a variety of applications. Clinically useful X-ray, electron, neutron and pion beams can be produced for cancer therapy. Processing machines can provide electron and X-ray beams for the chemical, plastics and food industries. CW and high duty cycle accelerators are being studied and developed for research in nuclear physics. Low and medium duty cycle accelerators are being built for storage ring and synchrotron injection, neutron spectroscopy, biology and a variety of other research uses. Current design concepts for these and other applications are described.

Introduction

The microwave electron linear accelerator was invented a quarter century ago.[1] The first machine was completed in England[2] in 1946 using a 2 megawatt magnetron to produce 100 mA at 3-1/4 MeV. A parallel effort at Stanford[3] eventually led to the development of the first high power pulsed klystron and then to an electron linear accelerator which produced a 35 MeV beam using 13 megawatts klystron power. Today several important industrial corporations can trace the origins of their power klystron business to this initial Stanford work. The Stanford group[3] went on to build the first multiklystron linac, initially producing 630 MeV with 20 klystrons. This early work in these research laboratories was so successful that industry was able to take over the continuing effort of machine development and production. Most of the subsequent work in the medium energy range has been performed by industrial firms of England, France, Japan and the United States. The major development effort by industry has been directed toward the application of the electron linear accelerator principle in a wide variety of fields.

Also a quarter century ago the microtron was invented.[4] The first microtron was completed in Canada[5] in 1948. Subsequently, microtrons have been built by research laboratories in half a dozen countries, with the most intense effort being carried on in Russia[6,7] and Sweden[8] on circular orbit machines and in Canada[9] on racetrack orbit machines. Kapitsa[7] in 1964 reported attainment of a 20 mA beam at 25 MeV with a 28 circular orbit microtron.

The availability of microwave power sources has, in a major way, determined the design of accelerator waveguide. Magnetrons, amplitrons and klystrons have been used as sources. Power levels have ranged from 1 to 30 MW peak and 1 to 65 kW average per tube. Frequency has ranged from 1300 to 9000 MHz. High stability of amplitude, frequency and phase are required, with pulsed operation at pulse lengths in the 1 to 30 μs range. Hence, multi-megawatt modulator pulse voltage stability of one or two parts per thousand and guide temperature control to 0.1°C have become accepted practice.

As with any other type of accelerator, the performance of linear accelerators and microtrons is determined in large measure by the quality of performance in the injection region. For linac operation in stored energy mode, injection systems are being developed to provide 15 amperes within a 30° accelerated bunch for pulse lengths from 2 to 24 ns. (All currents stated are averaged over the pulse length, not over the RF bunch length.) Similar systems have been studied which in theory would provide 100 amperes within a 60° accelerated bunch. For linac operation in steady state mode where minimum energy spread is desired, injection systems have been developed which will produce 200 ma within a 3° bunch and 500 mA within a 10° bunch. For circular orbit microtrons guns have been developed with emission density of 150 amperes/cm^2 and special injection orbits have been devised which permit subsequent energy gain per orbit of 1 MeV. For a 400 MeV racetrack microtron a separate 12 MeV linac has been proposed for injection.

Elementary Particle Physics

Electron linear accelerators are currently being built in the 80 to 300 MeV region as injectors for synchrotrons in the 6 to 10 GeV region and at energies to 500 MeV for injection into colliding beam storage rings. Figure 1 shows the injector for the 1.5 GeV electron positron storage ring being installed at Frascati, Italy. This linac has produced a 100 mA electron beam at 380 MeV with 80 mA within 1% energy bin. It has produced a 930 μA positron beam[10] at 347 MeV with 380 μA within 1% energy bin. Modulation of the beam at about 9 mc is provided to match the storage ring acceleration frequency. Beam duty cycle of 0.08% is provided for research directly with the linac and a program in meson physics is planned. Figure 2 shows the linac being built for injection of electrons and positrons at 300 MeV into the 7 GeV DESY synchrotron at Hamburg, Germany. The DESY group is working on a proposal for an electron positron storage ring.[11] It is proposed to use the linac for direct injection into the storage ring at 300 to 500 MeV for test purposes and then to use the synchrotron beam for injection in routine operation. A 20 ampere diode gun is being developed for use with a 500 mc chopper to provide one pulse in six modulation of the beam for synchrotron injection. The DESY linac will employ 12 S-band 24 megawatt klystrons and 12 accelerator guides each 5 meters long. The first five guides will produce a 320 mA 200 MeV electron beam at the positron converter. Four kilogauss solenoids over the next two guides and quadrupoles over the remaining guides will contain the positron beam. During positron operation two-thirds of the contaminating electron current will be removed by a rectangular collimator at the first beam waist at the quadrupole doublet which matches the phase space from the solenoids to the phase space of the quadrupole channel. A positron current of 1 mA within 1% energy bin at 300 MeV is expected using a nutating tungsten disk converter immersed in an 18 kilogauss short solenoidal field. Work is proceeding on the development of a pulsed horn type focusing system[12] which offers a theoretical improvement in positron beam current of a factor of 3 by accepting a large solid angle from a cylindrical converter. Figure 3 shows a schematic cross section of such a system. The horn is constructed of eight 0.3 by 1.0 mm silver alloy bars to provide about 80% transparency to the positron flux.

Nuclear Physics

Figure 4 shows an L-band electron linac being built for Oak Ridge National Laboratories. One major use will be in neutron spectroscopy in the several hundred keV neutron energy region to develop data for the fast breeder reactor program. Beam current of 15 amperes at 156 MeV will be provided in pulse lengths from 2 to 24 nanoseconds at repetition rates to 1000 pps. With 24 nanosecond pulse length, the fast neutron yield from a non-multiplying U-238 target is about 2×10^{11} n/pulse and 2×10^{14} n/sec at 1000 pps. With a multiplying target a fast neutron yield of the order of 10^{16} n/sec should be attainable. A 50 ampere 150 kV triode gun is being developed for this machine. Four L-band 30 megawatt klystrons are used. Solenoids will produce a 2 kilogauss field over the bunching region and 1 kilogauss over the remainder of the accelerator guide. The four accelerator guides are each 14 feet long.

Several laboratories are interested in studying nuclear structure by electron scattering using coincidence techniques. About 400 MeV appears to be adequate electron energy for much of this work. Good energy resolution of the electron beam is generally desired so that by subtraction of the energy of the inelastically scattered electron the energy given to the nucleus can be known to good accuracy. High duty cycle is required in order to avoid pile-up in coincidence detection apparatus. The typical duty factor of most linacs has been in the 0.01 to 0.1% range. The M.I.T. group is building a machine at 1.8% duty cycle. A linac capable of 600 MeV unloaded energy at 1% duty cycle is being built by CSF for the Saclay laboratories in France at a price of about $8 million. Normal conductivity machine designs are under consideration with duty factors up to 10% at a cost in excess of the Saclay price. It appears to be possible to build a 400 MeV 10% duty cycle normal conductivity racetrack microtron for a small fraction of this cost. Beam phase-orbit calculations indicate that such a microtron may be capable of providing an average beam power of the order of 5 kW with an energy spread at half intensity of 0.01% and of the order of 50 kW with an energy spread of 0.1%. For comparison, the Frascati linac produces a 400 MeV electron beam of 25 kW average power with energy spread at half intensity of 0.5%. It should be possible to design a high duty cycle linac to produce a 100 kW beam with an energy spread of 1/4 % and to select 5 kW of this beam within an energy spread of 0.02 % using a spectrometer. Since the bunch width in such linacs is expected to be only 2 or 3 degrees, it should be possible to make a further improvement of a factor of 2 or 3 by use of large radius magnet system which debunches the beam as a function of energy, followed by an accelerator section phased to provide zero energy gain for the desired energy. In essence, such a system is somewhat equivalent to the last orbit of a racetrack microtron and comparable energy resolution should be obtainable. Thus, it should be possible to achieve comparable beam performance with either a linac or a microtron. The reliability and flexibility of the 400 MeV racetrack microtron concept remains to be demonstrated.

Chemistry Research

A free radical is an atom or molecule with an uneven number of electrons such that the odd electron spin is unpaired. The free radical is chemically highly reactive since it combines readily with another atom or molecule to pair electron spins. The hydrogen atom is an example of a free radical; it combines readily with another hydrogen atom to form a hydrogen molecule in a lower energy state than the two independent hydrogen atoms. It takes several electron volts of energy to increase the energy of the molecule such that it breaks apart into free radicals; a penetrating electron beam is an excellent source of energy for production of free radicals. A beam energy of 5 to 15 MeV is desired for adequate penetration of the chemical and its containers. The concentration and recombination rate of free radicals can be detected with high sensitivity by shining light through the sample and observing the magnitude and rate of decay of absorption at specific wavelengths. However, for specific identification of the free radical chemical arrangement, it would be desirable to use an electron spin resonance spectrometer, which typically employs a small microwave source at X-band to provide energy to flip electron spins in an orienting magnetic field. The population of unpaired resonant spins is detected by the reactive or resistive load change produced by the chemical sample in the microwave cavity as its unpaired electrons absorb microwave power. Figure 5 shows a spin resonance spectrometer arranged for use with a small linac.

In chemical reactions, a chemical may change from stable state A to stable state C through intermediate transient state B. The free radicals which provided the energy for the reaction existed in state B. Since the free radicals are highly reactive they recombine readily and have short lives, often in the range of milliseconds to seconds in solids and nanoseconds to milliseconds in liquids. Present spin resonance equipment response time is of the order of milliseconds. Thus, with presently available equipment a solid placed in the microwave cavity of a spin resonance spectrometer can be irradiated by a single pulse from a linac to produce free radicals and their reaction kinetics can be studied by observing the decay rate of the signal. Free radical reaction kinetics in liquids is of much greater interest and work is proceeding on development of spectrometers with response time in the microsecond region. In this case, the signal-to-noise ratio of the spin resonance equipment is enhanced by operating the linac with microsecond beam pulses at a rate of about 1000 pps and by using signal enhancing techniques at this rate. For free radical lifetimes in the region of 1 μs, linac beam pulse rates in the 10^5 to 10^6 pps range would provide increased sensitivity. This could be achieved with a CW linac or microtron and gated gun.

Medical Applications

Shortly after the discovery of X-rays, they were tested on cancer. Over the decades, 250 kV X-ray machines became a preferred tool for treatment of cancer. However, higher energy X-rays were desired to permit treatment of deep-seated tumors without the patient sickness produced by excessive dose to normal intervening tissue and skin. With the advent of nuclear reactors for production of weapons materials, radioactive Cobalt-60 became available; it emits 1.1 and 1.3 MeV gamma rays. Cobalt-60 is now replacing 250 kV X-ray machines for treatment of deep-seated tumors. The radioactive Cobalt loses 13% of its activity each year and is usually replaced after 3 or 4 years.

Microwave electron accelerators at about 4 to 8 MeV are becoming widely used for X-ray cancer therapy. These machines offer advantages over Cobalt-60 such as higher intensity, constant intensity, more penetrating beam, and more accurately defined X-ray field because the electron focus on the metal target produces a much smaller X-ray source than the diameter of a pellet of high intensity radioactive Cobalt. Some of these machines also provide an electron beam for direct electron treatment of superficial lesions. The advantage of the electron beam in this application is that the electrons have a finite range and the normal tissue beyond the chosen treatment depth is relatively unexposed to radiation. Higher energy electrons, up to about 35 MeV, are useful for the same reason in the treatment of deep-seated tumors. A few microwave electron accelerators have been used for many years for direct electron irradiation at energies as high as 70 MeV and standard 35 MeV units are now being developed by industry.

If malignant tumors are detected early enough and metastisis does not occur, the probability of cure with modern irradiation equipment in the hands of properly qualified radiotherapists is relatively high for certain types of cancer. The development of methods for earlier detection of cancer on a wider population basis offers great potential for control of cancer. One such method is to employ short lived radioisotopes and gamma ray cameras for general screening of large segments of the population. The use of short lived isotopes is essential to minimize radiation dose to the patient and to minimize gamma camera viewing time. They must be produced locally and this can be done at night using the X-ray beam of a 35 MeV linac normally used for therapy during the day.

A typical total dose given to a tumor is 6000 rad, fractionated into 20 daily doses of 300 rad each. This fractionation appears to be essential in differentiation between normal cells and cancer cells. The normal tissue cells respond to the new environment of being irradiated; they increase their growth rate and repopulate rapidly after each exposure. (This is illustrated by the rapid healing of a cut finger.) The surviving tumor cells go on growing at an unaltered rate since they are not under the control of the body.

In order to minimize the damage to normal tissue, efforts are made to concentrate the X-ray dose in the tumor by irradiating it from more than one direction. Figure 6 shows a treatment plan with exposure from three ports. Figure 7 shows a 6 MeV X-ray machine capable of 360° rotation about the patient to facilitate multi-port field treatment.

In practically all tumor tissue there are anoxic (absence of free oxygen) regions, resulting from the growth of the tumor interfering with its own supply of blood. In fully oxygenated cells irradiated with X-rays or electrons, most of the cell deaths occur due to chemical action of peroxides on long chain molecules in the cell nucleus. In anoxic cells peroxides are not as readily produced by radiation. To kill these anoxic cells requires 2.7 times the dose, which would be disastrous on healthy tissue surrounding the tumor. If a way could be found to kill the anoxic cells of the tumor without producing an excessive dose in surrounding normal fully oxygenated tissue, improved results of cancer therapy might be obtained. This would not solve the problem of distant metastisis but it might reduce the probability of regrowth of the tumor from surviving anoxic cell sites.

Cells irradiated with highly ionizing heavy particles such as protons below about 2 MeV and alpha particles below 5 MeV are killed primarily by a direct process of depolymerization of long chain molecules, with chemical effects by peroxides being of secondary importance. Thus, these particles kill anoxic and oxygenated cells with roughly equal efficiency. Since they must be low energy to have sufficient ionization intensity, they are not penetrating enough to be sent in from outside the patient but must originate inside the tumor. One method is to irradiate the patient with a neutron beam of about 7 MeV. The neutrons produce knock on protons which are highly ionizing. However, the dose falls off more rapidly with depth than with an X-ray beam, so the advantage over X-rays becomes marginal for the most deeply seated tumors. Another method described by Fowler[13] is to irradiate the patient with a π^- beam. The π^- have a finite range so by choice of energy and energy spread they can be brought to rest throughout the tumor volume with very little dose being given to surrounding tissue. When a π^- comes to rest it is captured by a nucleus. The 140 MeV rest mass of the π^- is given up to the nucleus, producing fission. Seventy-three percent of captures in tissue are by oxygen nucleii. In the oxygen fission, 40 MeV is given to binding energy of the fission fragments and 100 MeV is given to kinetic energy, distributed on average as 5 MeV in particles of charge 3 and higher, 8 MeV in charge 2 such as alphas, 16 MeV in protons, deuterons and tritons and 70 MeV in neutrons which in turn produce knock-on protons of 2.4 MeV average energy, alphas and heavier particles. The fission fragments are highly ionizing. Thus a π^- beam has the double advantage of killing anoxic tumor cells without excessive dose to oxygenated cells of normal tissue and the dose can be concentrated in the tumor with minor dose to surrounding tissue. Figure 8 shows typical tracks produced in photoemulsion as a result of nuclear fission from π^- capture. Figure 9 shows the computed dose distribution produced by a 52 to 68 MeV π^- beam terminating at 10 to 15 cm depth and shows its relative efficacy in anoxic cells when compared to other beams such as X-rays and protons. The pion beam described here could be produced with a 50 kW 400 MeV linac or microtron electron beam striking a high Z X-ray converter followed by a low Z photo-pion converter, a pion horn and a momentum discriminator.

Industrial Applications

Sterilization of Drugs and Medical Supplies

Irradiation sterilization is more expensive than conventional methods and is justified only where offsetting benefits accrue in quality, packaging or handling of the product. In many cases, use of irradiation sterilization instead of heat sterilization permits the substitution of a superior or cheaper but heat-sensitive product. An example of a product suitable for industrial irradiation is absorbable surgical suture, popularly called catgut and derived from the connective tissue layers of the intestines of sheep and cattle. This material is protein and is very sensitive to heat, particularly in the presence of water. The conventional process is to dehydrate the sutures, heat sterilize, rehydrate, and package. With substitution of irradiation, dehydration is not required and the sutures are irradiation-sterilized in their final packages. Another example is irradiated throw-away plastic syringes in place of glass syringes which must be heat-sterilized after each use. The irradiation facility of Figure 10 has been used extensively in this latter application as well as for food irradiation research.

Food Processing

Fresh foods are normally preserved by steam canning to destroy micro-organisms or by refrigeration to slow their reproduction. The steam canning process cooks the food so that it no longer tastes fresh. The refrigeration process is costly and inconvenient both for transportation and for storage.

Fresh foods can be preserved by destroying the micro-organisms with radiation. The temperature rise in the food is only a few degrees. The most radiation resistant micro-organism is clostridium botulinum, a spore former and the cause of potentially lethal botulism. A dose of 4.5 megarads in non-acid low-salt foods is required to reduce the population of this micro-organism by 10^{12}, sufficient to ensure complete destruction and comparable or superior to the population reduction achieved with steam canning. The sterilized product, if properly packaged, will keep indefinitely. At lower doses, pasteurization is achieved, with resultant extended shelf life.

The production rate of a large steam canning line is typically 20 tons per hour. At 5 megarad average dose for sterilization and 60% efficiency of utilization of the electron beam in the package of food, a 50 kW microwave electron accelerator will process 2.4 tons of food per hour. At 1/2 megarad typical dose for pasteurization, the same machine will process 24 tons per hour.

Plastics

Plastics consist of long chain hydrocarbon molecules with 4 bonds per carbon atom and 1 bond per hydrogen atom. A bond comprises the sharing of an electron by two atoms and the resulting molecule is in a lower energy state than the individual atoms. Irradiation provides energy to break bonds, producing ions and free radicals which on recombination result in modification of the initial hydrocarbon molecule atomic arrangement. Such rearrangements are classified for example as polymerization, cross-linking, grafting, etc.

Heat shrinkable plastic film, sheet and tubing, for encapsulation of food, electronic components, etc., is produced commercially by irradiation. The plastic is stretched to orient the polymer molecules and irradiated to crosslink them, thereby holding them in their stretched positions. On heating, the viscosity of neighboring polymer molecules is reduced and the plastic shrinks toward original size, encapsulating the product. Crosslinking by irradiation is also employed to increase the thermal resistance of wire insulation and plastic tubing.

Irradiation has been used experimentally to produce wrinkle-resistant clothing by grafting the cellulose molecules of the cloth to polymer molecules.

X-ray Inspection

The electron linear accelerator is used for production of an intense penetrating high-energy X-ray beam for radiographic inspection for flaws in thick objects such as missile solid propellant and nuclear reactor vessel weldments. The electron beam is focused to 1 or 2 millimeters diameter on a rotating water-cooled heavy metal target, producing X-ray beam intensities up to 25,000 R per minute at 1 meter. Good resolution has been obtained through as much as 2 feet thickness of steel with the machine shown in Figure 11.

Conclusion

In conclusion, we can divide the development of medium energy microwave accelerators into three stages, past, present and future. In the past, one area of major development effort has been on low duty cycle linacs at 50 to 500 MeV for use as injectors for circular machines and for direct use in research. A second major area has been on machines at 5 to 50 MeV for cancer therapy and for industrial applications. Currently the major development efforts are on 1 to 2% duty cycle linacs at several 100 MeV, on nanosecond type beams at currents to 15 amperes and on improved reliability and reduced cost of machines for medical, chemical and industrial applications. Microtrons and superconducting accelerators remain interesting potential development areas for the future.

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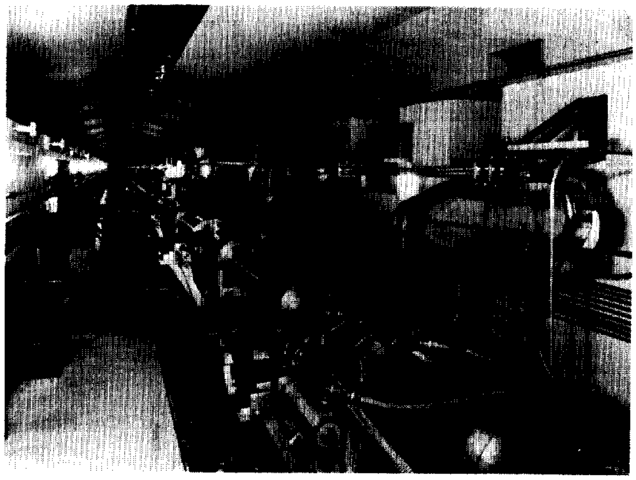


Fig. 1. Frascati Linac in Tunnel.

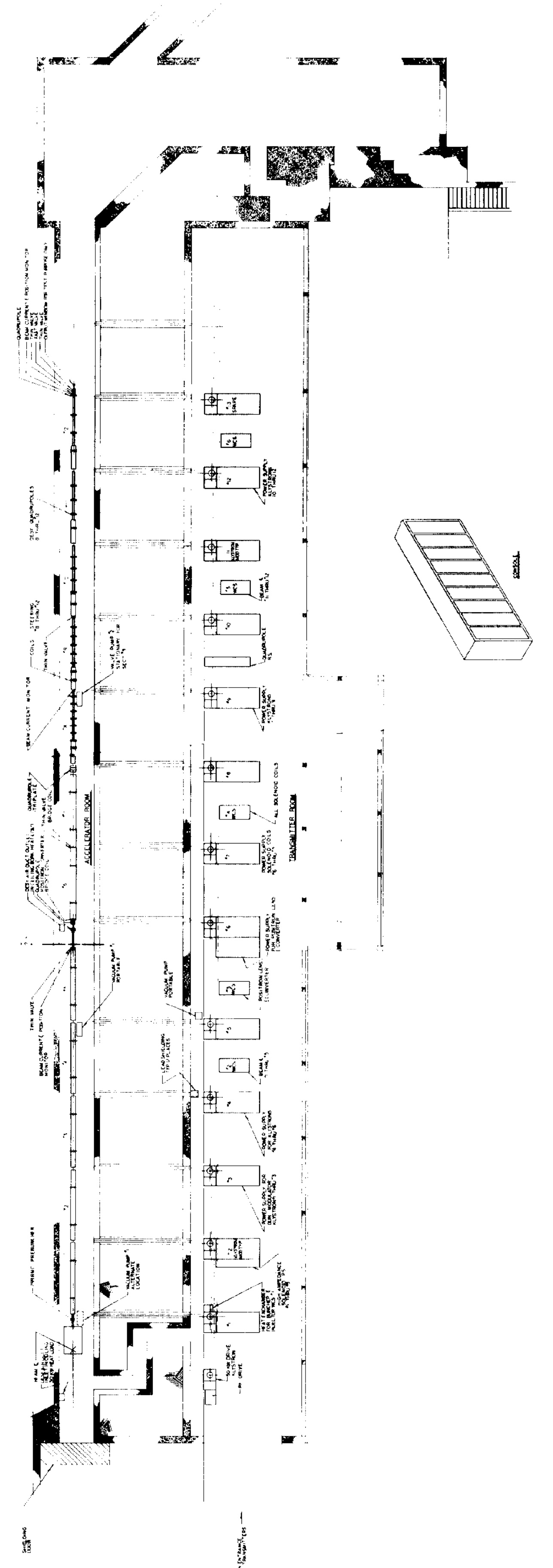
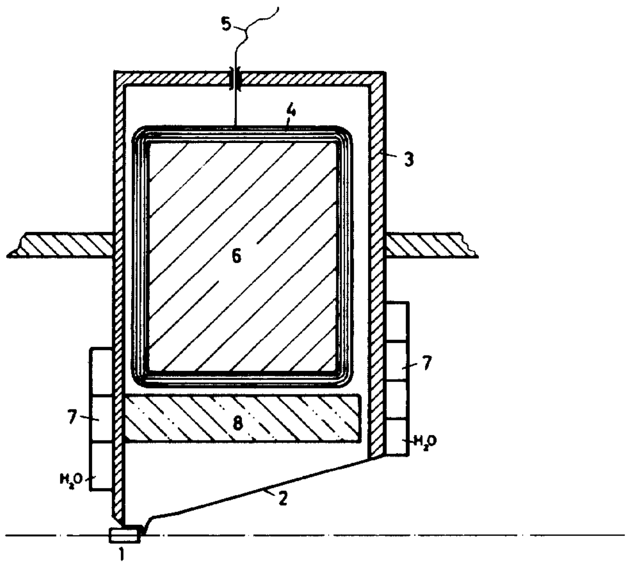


Fig. 2. DESY Linac Layout.



1 Target
2 Positronenhorn
3 Sekundärwindung-Gehäuse
4 Primärwindungen
5 Primäre Energiezuführung
6 Kern
7 Kühlung
8 Bleischutz

Fig. 3. Positron Horn Converter (From Ref. 12).

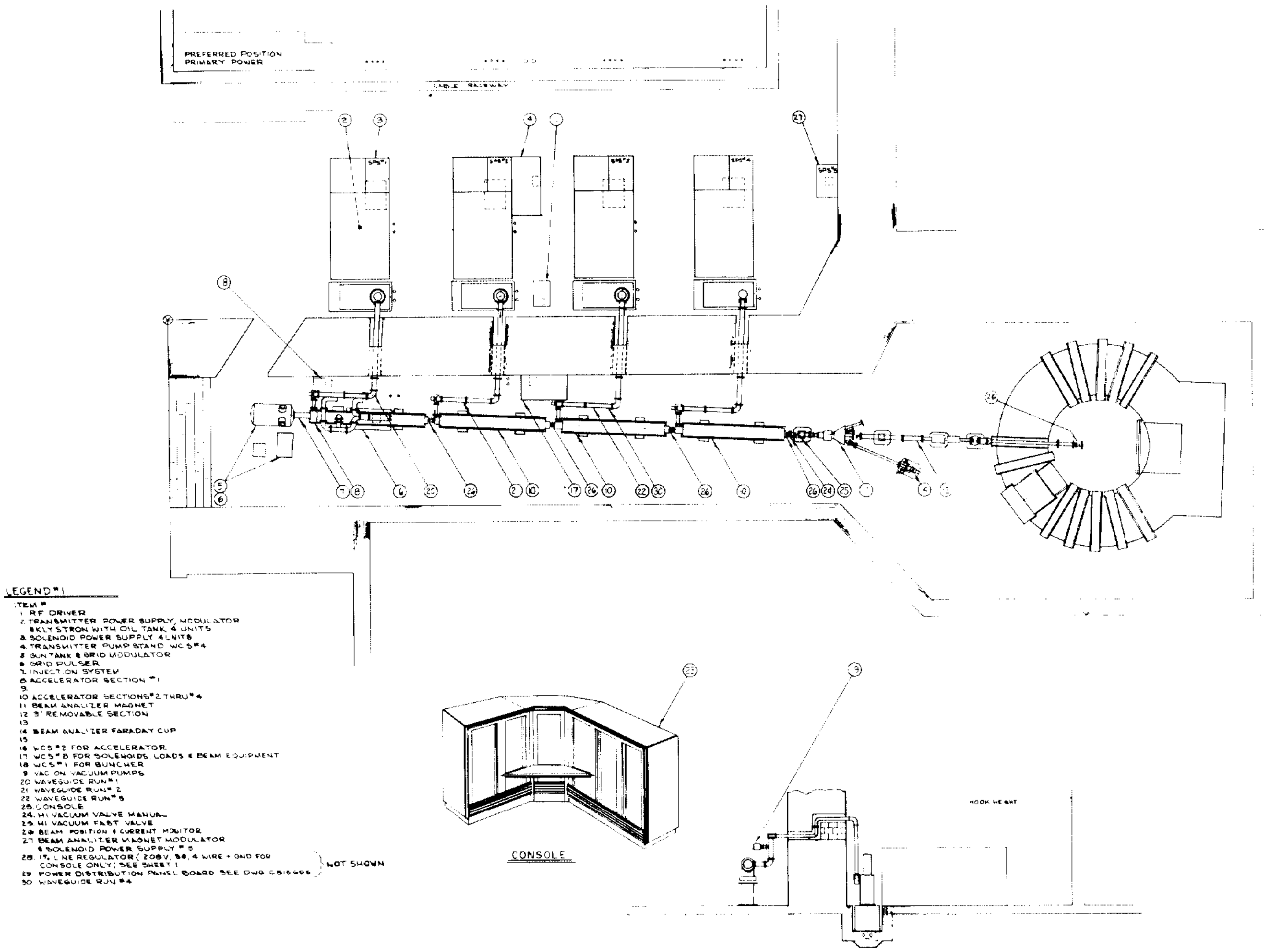


Fig. 4. Oak Ridge Linac Layout.

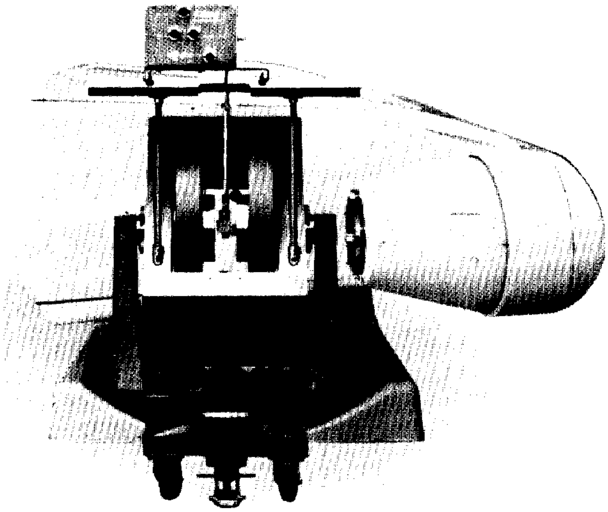


Fig. 5. 6 MeV Linac and EPR Spectrometer for Free Radical Kinetics Studies.

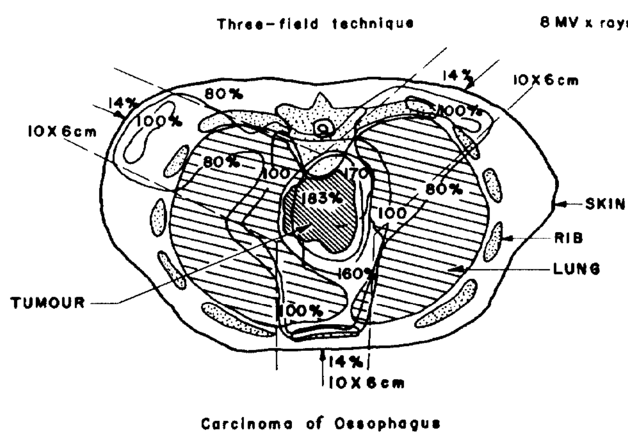


Fig. 6. Isodose Distribution for Three-Field X-Ray Cancer Therapy (From Ref. 13).

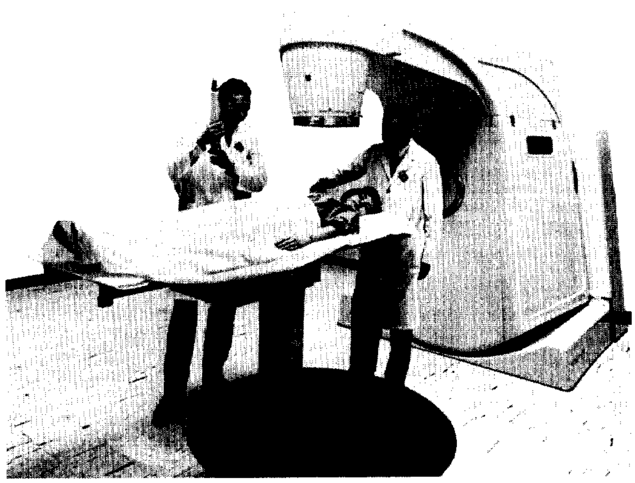
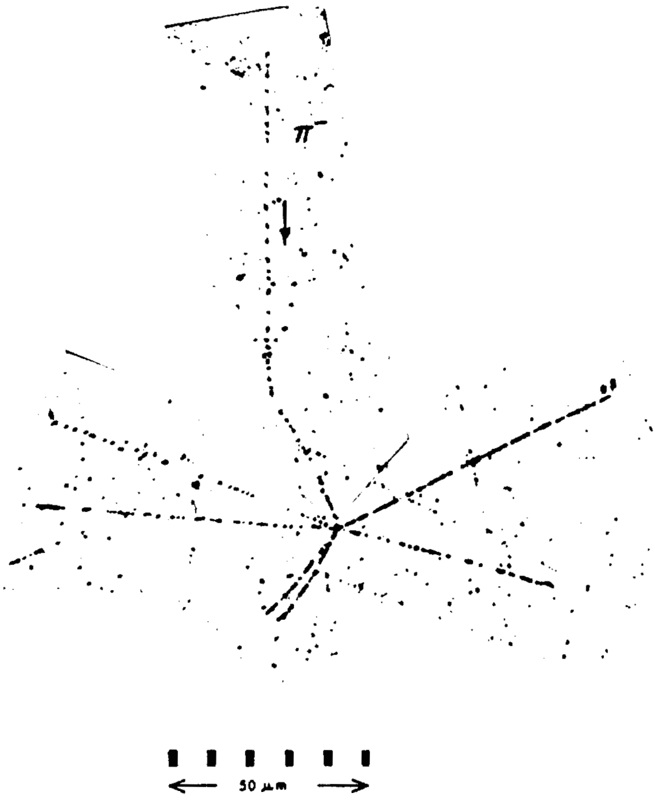


Fig. 7. 6 MeV Linac for Cancer Therapy.



An example of π^- capture by oxygen nuclei. The example shown is chosen to illustrate the distinction between the tracks of α particles and protons of the same range. Coming clockwise from the π^- meson, the first track is that of an α particle of 9 MeV and the second that of a proton of 1·7 MeV. Both these tracks are in the plane of the emulsion. The next two tracks of singly charged particles appear dense in projection as they dip at about 45° to the emulsion plane. The two left-hand tracks are flat, but do not terminate within the field of view.

Fig. 8. Fission from π^- Capture in Oxygen (From Ref. 13).

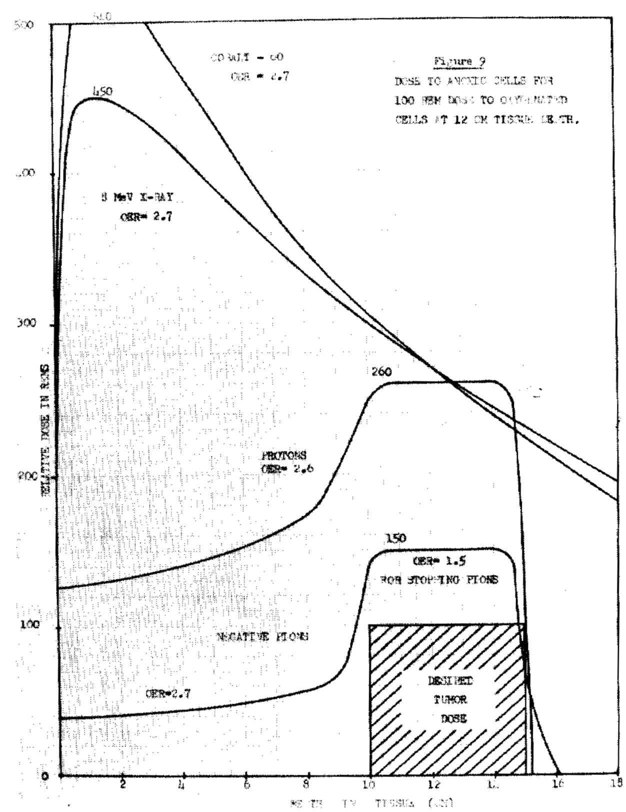


Fig. 9. Anoxic Cell Dose.

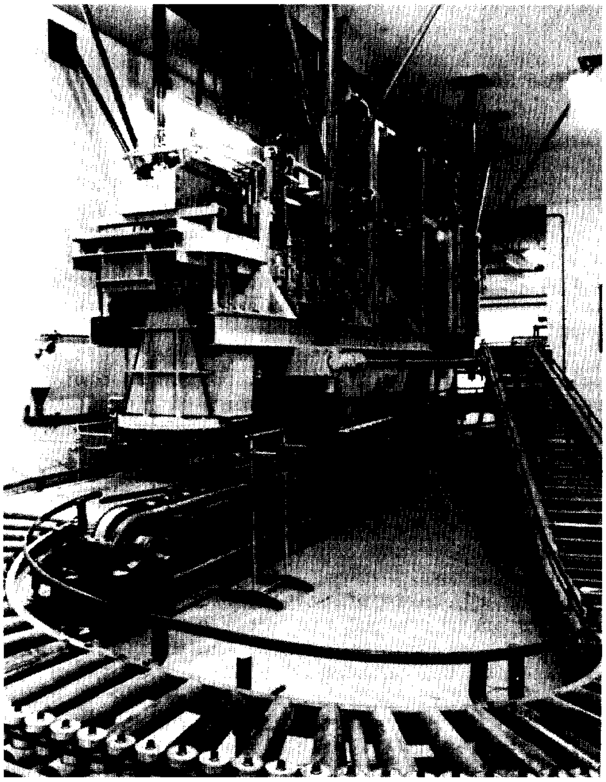


Fig. 10. 10 MeV Linac for Irradiation Processing.

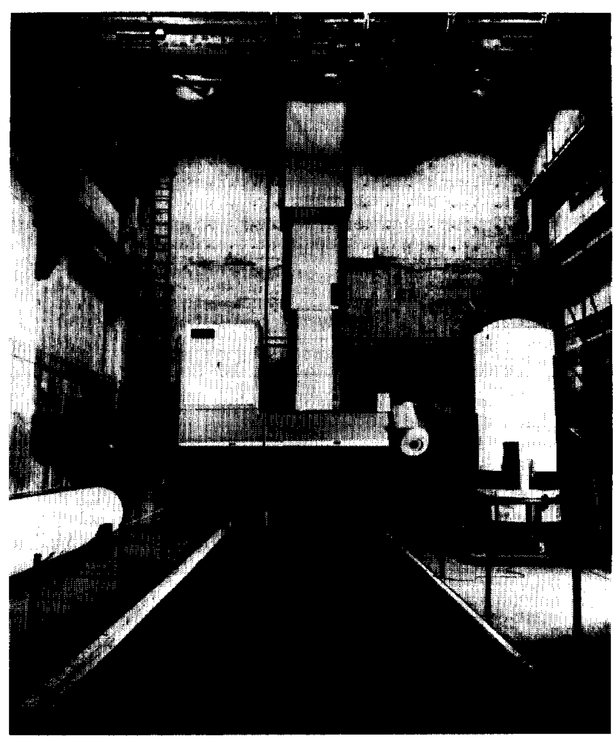


Fig. 11. Linac for X-ray Inspection.